DETAILED SPECIFICATIONS OF THE ATMOSPHERE FOR INFRASOUND PROPAGATION MODELING

Douglas P. Drob

Naval Research Laboratory

Sponsored by Defense Threat Reduction Agency

Contract No. DTRA-MIPR-02-2317

ABSTRACT

To model infrasound propagation accurately, detailed knowledge of the background atmospheric state variables—regional wind, temperature, pressure, and density fields from the ground to approximately 170 km—is required. Providing these specifications is a difficult problem, partially because the atmosphere is a complex medium, which varies on time scales from several hours to several months, and over horizontal scales of about 750 km. Several government agencies (e.g., NOAA, NASA, USAF, etc.) build and maintain operational networks of ground-based weather stations and satellites to monitor the lower atmosphere. Using the combination of rigorous statistics and geophysical fluid dynamics, these observations are continuously assimilated into numerical models to produce detailed numerical weather specifications and predications (NWP). These NWP products are typically updated several times daily, have spatial resolutions exceeding 1ºx 1º, and can range from the surface to near 55 km. For the middle and upper atmosphere (>55 km), however, there are currently no operational measurements or NWP products available. Fortunately, sparse and sporadic scientific data have often been available. From these data, reliable empirical atmospheric models can be constructed. Two such models are the Naval Research Laboratory, Mass Spectrometer and Incoherent Scatter Radar (MSIS) model and the Horizontal Wind Model (HWM). The crux of the problem in providing detailed specifications of atmosphere for infrasound propagation modeling lies in combining the various pieces of available information into a single coherent specification which can be applied to an arbitrary time, location, and altitude. To meet this challenge a unique atmospheric specification system is being developed. The Naval Research Laboratory, Ground to Space semi-empirical spectral model (NRL-G2S) produces high-resolution global atmospheric specifications ranging from 0 to 170 km that are seamless and self-consistent. The specifications are currently being produced on a case-by-case basis for ground-truth events, as well as every 6 hours in near real-time. These new specifications introduce a great deal of complexity into infrasound propagation modeling results. This complexity arises from the highly structured spatial and temporal variability of the atmosphere as specified by the historical and near-real-time operational data. It is asserted that it is both necessary and possible to account for this complexity. This is demonstrated with global maps of local ducting fractions calculated from the HWM/MSIS and NRL-G2S models. The resulting information provides a comprehensive picture of the variability and coupling of atmospheric regions as it relates to infrasonic signal propagation. In operational event detection and location applications, these novel calculations might potentially provide a means to assess possible propagation paths quickly.

OBJECTIVES

The objective of this work is to provide detailed specifications of the atmosphere from the ground to space for nuclear explosion monitoring. Infrasound propagation calculations require specifications of the atmospheric state variables U, V, T, r and P (the wind components, temperature, mass density, and pressure) from the surface to approximately 170 km. In addition, these specifications are needed in near real-time for operational processing and on a case-by-case basis for the analysis of historical events. These specifications should be global in nature and have enough temporal and spatial resolution to provide a meaningful advantage over the existing climatological models in use. Compared to static propagation mediums, the complexity of the atmosphere seems daunting. It requires a concerted effort to understand, manage, and utilize the required information effectively. In addition, the complexity of this information tends to increase when integrated into propagation codes and monitoring systems. These atmospheric specifications should obviously be robust, self-consistent, and as accurate as possible. One problem is that this information can easily be called into question because the uncertainties needed to qualify the information are often even more complex. An additional general requirement is that the software tools for working with atmospheric specifications be simple, functional, and reliable. Extraneous environmental information may overburden operational monitoring systems or even unduly alter the interpretation of a suspected event.

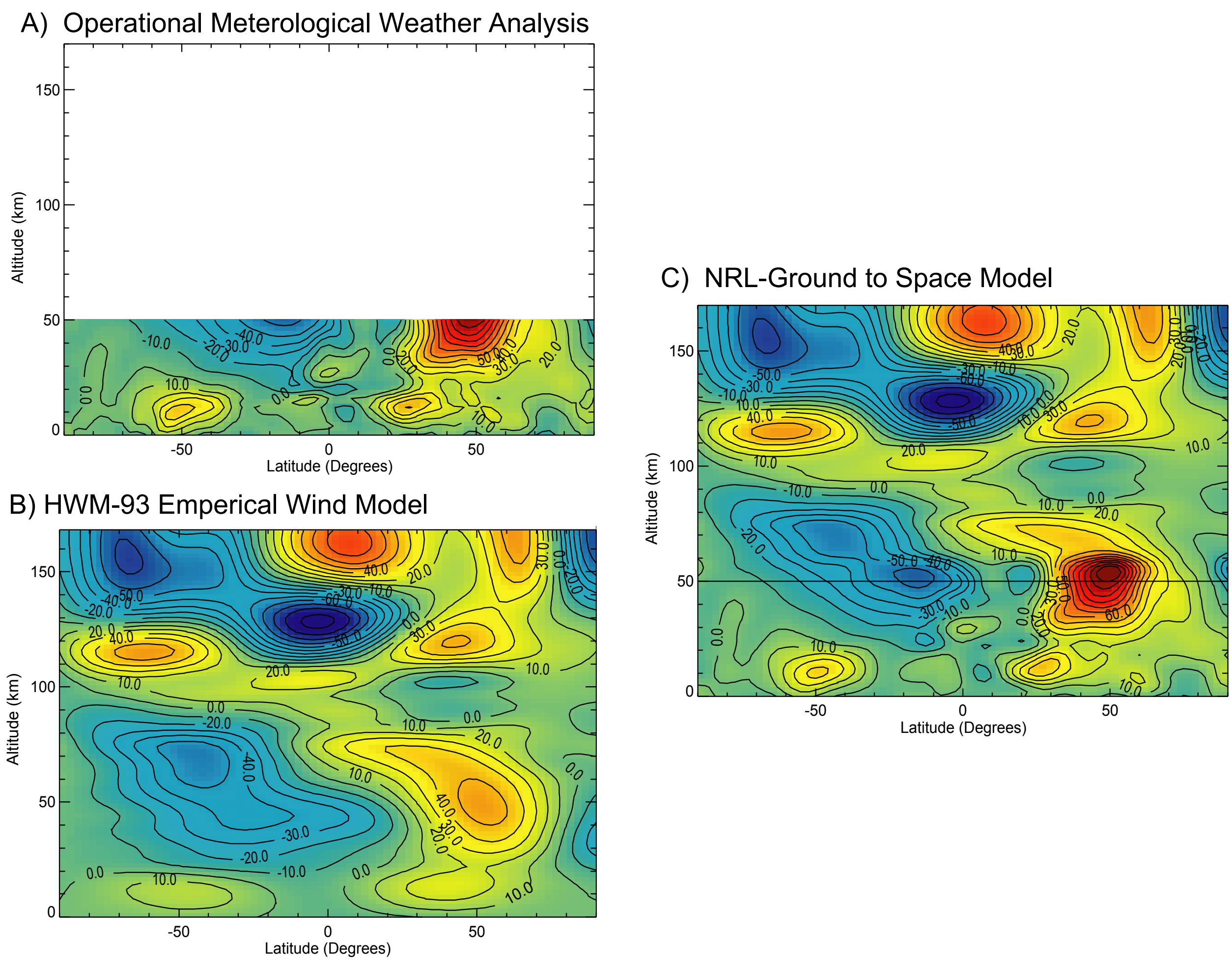

Figure 1. Three typical atmospheric specifications of the eastward wind velocity component (zonal) at 120º E on January 31, 1999, at 12:00 UTC; A) Numerical Weather Predication analysis products (e.g., NOAA-NCEP), B) the HWM-93 empirical wind model, and C) the NRL Ground to Space (G2S) semi-empirical spectral model.

RESEARCH ACCOMPLISHED

To meet these objectives a next-generation atmospheric specification system that fuses state-of-the-art empirical models with operational meteorological analysis products has been developed. The system produces a global current-time specification that is seamless, physically self-consistent, and easy to use. Special care is taken to ensure that no spurious artifacts are introduced into the atmospheric specifications during the data fusion process.

Data Fusion System

Figure 1 illustrates the current state of affairs with respect to available atmospheric data. It shows three different data based specifications for the zonal (eastward) velocity component of the wind as a function of altitude and latitude, at 120º E, for January 31, 1999, 1200 UTC. The zonal wind-field is an important factor in determining whether tropospheric, stratospheric, or thermospheric ducting of infrasound signals occurs. Panel A shows a typical near real-time meteorological analysis specification, here provided by the NASA Global Modeling and Assimilation Office. The near real-time aspect and fidelity of the data is certainly desirable for improving the accuracy of nuclear detections through infrasound. Unfortunately, the specification does not extend to thermospheric altitudes. Panel B shows the most common ground-to-space specification available—the HWM-93 empirical/climatological model (Hedin et al., 1996). While extending over the entire domain, many of the details of the atmospheric state, captured by the near real-time specification, are missing from the climatological model. Panel C shows how the G2S system preserves and extrapolates the details of the meteorological analysis to higher altitudes using the context provided by HWM, while simultaneously combining the two parameter sets into a coherent seamless global field. The salient features of both specifications are discernable in the fused G2S specification results. Our methodology represents an extension of the meteorological specifications into space, or alternatively an assimilation of meteorological data into the empirical models. The G2S system is also capable of assimilating raw observations not yet incorporated into the meteorological specifications or upper atmospheric models. In future versions geophysical fluid dynamic constraints can be applied during the fusion processes to improve the accuracy of the results.

The underlying mathematical formulation of the G2S model is as follows. Depending on the region and nature of available data, the horizontal variations of the state-variables are decomposed into spherical and vector spherical harmonics (SH/VSH). These data fields are typically the meteorological specifications and correspondingly gridded empirical model output fields from the HWM-93/NRLMSISE-00 models (Hedin et al., 1996, Picone et al., 2003). Where we have regularly spaced input data, Fourier transform methods are used to determine the SH/VSH coefficients. Were unevenly sampled ground- and/or satellite- observations available, direct linear-matrix inversion methods could be used to estimate the spectral coefficients. This method includes the use of error weighting and sidesteps the need to interpolate different types of observations having different granularity.

Our system can go one step further in that the thermospheric temperature and density output fields from the NRLMSISE-00 model can be dynamically tuned to agree with historical and operational UV satellite imaging and limb-scanning observations. At a centralized location, information from near real-time UV observations can be used to generate epoch dependent MSIS model correction factors. These factors dynamically renormalize the internal global temperature distribution and output densities of the models. Data from the DMSP-SSULI and SSUSI instruments, to be launched later this year, will be used to implement and validate this technique.

Once the SH/VSH harmonics coefficients are determined at all levels throughout the atmosphere, each spectral coefficient (n,m) is fit with rational B-splines in the vertical direction using an error-weighted least-squares estimation procedure. We perform these operations in a vertical pressure coordinate system. It is easier to impose dynamical constraints during the data assimilation process in this coordinate system. Available meteorological fields are also distributed on pressure surfaces for the same reason. For nuclear monitoring applications, however, the G2S specifications are needed in altitude coordinates rather than on pressure surfaces. This is a minor problem overlooked by operational meteorological centers. To map subsequent results from pressure surfaces to geometric altitude an extra atmospheric state variable is needed. Geopotential height specifies the altitude at which a given pressure level occurs over a given location.

Sample results of the vertical SH/VSH fitting stage, for the single harmonic order (n,m) = (1,3) are shown in Figure 2. Here B_r (1,3) and C_r (1,3) are the real parts of the rotational and solenoidal VSH coefficients of the vector wind fields. T_a (1,3) and Z_a (1,3) are the real parts of the SH coefficients for the temperature and geopotential height fields, respectively. Once the rational B-spline coefficients have been estimated for all the SH/VSH harmonics out to some spectral order, the coefficient sets are archived and distributed by the NRL assimilation system. The maximum spectral order is ultimately limited by the effective resolution of the raw data sets. Different model resolutions are also used to optimize G2S data storage and transmission requirements.

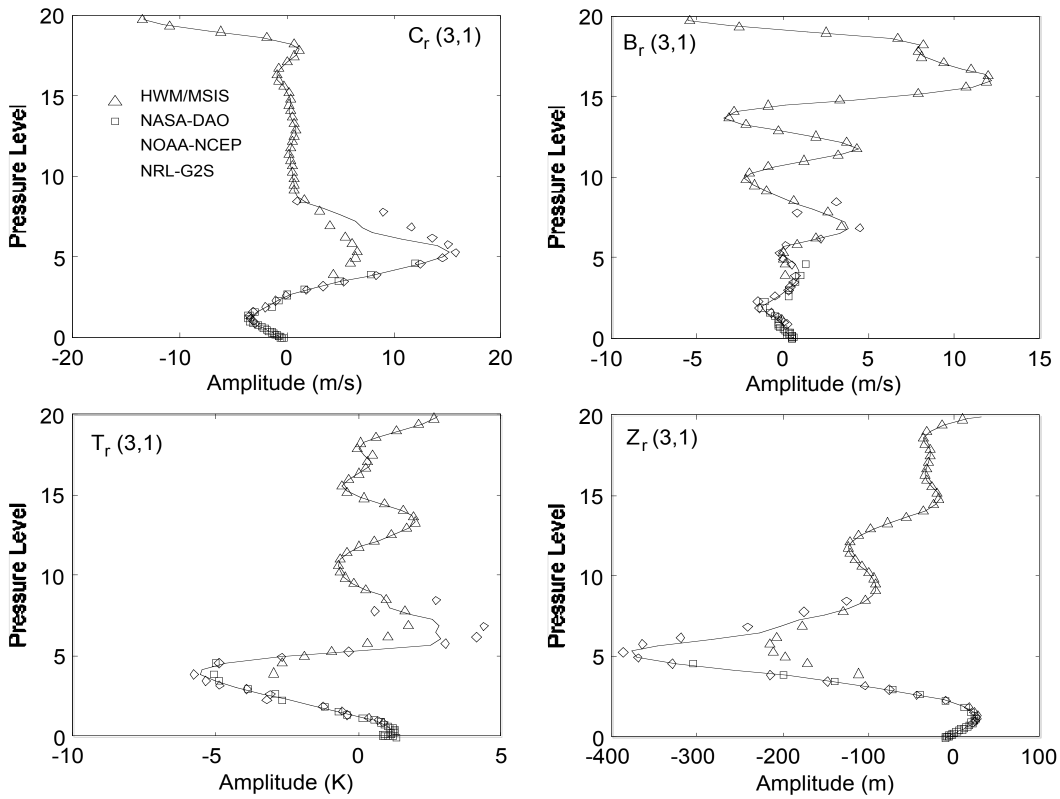

Figure 2. Examples of vertical SH/VSH fitting stage for (n=3, m=1) using transformed January 1, 2003, 12:00 UT data. The raw data sources are from the; NOAA/NCEP reanalysis products extending from 1,000 to 10 mb (0–35 km) (squares), NASA-DAO analysis from 400 to 1 mb (10–50 km) (circles), and the HWM-93 and MSISE-90 empirical models >10 mb (triangles). B_r and C_r are the real parts of the rotational and solenoidal VSH coefficients of the wind field. T_r and Z_r are the real parts for the temperature and geopotential height fields SH coefficients.

Client-Side Software

A set of precompiled software routines that perform the appropriate inverse spectral transforms needed to generate atmospheric specifications from the splined coefficients are provided to G2S model users. Here emphasis has been placed on developing the core environmental data processing routines, rather than graphical user interfaces, as there are several commercial and open source software tools available for visualizing complex 2- and 3-D global data sets. The BBN InfraMAP tool kit is one such example with particular relevance to nuclear monitoring (Gibson and Norris, 2002).

For a given event, or in near real time, individual G2S coefficient files are generated by the assimilation system at NRL-DC and distributed accordingly. A single G2S coefficient file encapsulates all of the information needed to reconstruct the temperature, pressure, total mass density, and the two components of the horizontal wind from 0 to 200 km anywhere over the globe for a given time. The G2S binary data files are also platform independent. This methodology encapsulates and compresses the information providing a very efficient way to store, transmit, and reconstruct large global volumes of environmental data.

The current client software has been optimized to provide vertical atmospheric profiles anywhere over the globe. From within MATLAB, the user first calls an external function library to load a specific G2S coefficient set into shared memory. Then given the input arguments of a spectral truncation and the global coordinates (lat,lon), the routines return vertical profiles of temperature, winds, pressure, and total mass density. From these fields the effective sound speed in the direction of wave propagation can be calculated as; $C_{eff} = sqrt(g*P/r)+ V_x*cos(\square) + V_y*sin(\square)$. Here $\square$ is the direction of propagation, V_x is eastward (zonal) wind component, and V_y in the northward (meridional) wind component, g = 1.4 is the approximate ratio of specific heats, P is pressure, and r is the total mass density. Figure 3 shows a sample output from the G2S specification system. The default vertical resolution of the nominal profiles is 1 km and ranges from 0–170 km. Multiple function calls can easily be made to construct 2- and 3-D fields. Precompiled binary libraries - G2Slib.a (Solaris) and G2Sclient.lib (Windows) have also been built for use with FORTRAN and C/C++ source codes.

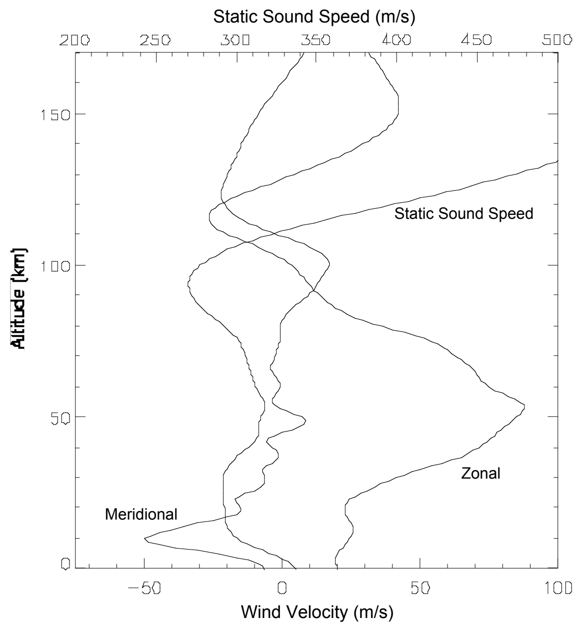

Figure 3. An example output from the G2S specification system outputs.

Additional features of the G2S client software include estimates of the surface altitude relative to mean sea level, i.e., a topographical model. From the client software, it is possible to obtain the corresponding HWM/MSIS model outputs for direct model comparisons. Information on internal G2S file content, such as time stamping and system version numbers can also be accessed with the software. A programmers guide and example codes are also available. Version 1.1 of the client software has been successfully integrated into both the Windows and Solaris versions the Tau9 (Garcés et al. 2002) infrasound propagation software package. The G2S client software is also being integrated into the BBN InfraMAP tool kit (Gibson et al. 2002). Several other institutions have also utilized the G2S client software as a stand-alone package in their research. These efforts will complement existing work to integrate near real-time environmental model capabilities into infrasound propagation modeling calculations.

<u>G2S-E and G2S-RT</u>

For interactive event analysis, we found that it is important to generate a G2S coefficient set that corresponds as closely as possible to the estimated event time. These files are referred to as G2S-E files (E for event). For a variety of different infrasonic ground-truth events covering 1998 to the present, a significant number of G2S-E coefficient files have been generated. G2S-E files are generated for ground-truth events as early as 1992. In special circumstances, it is even possible to go as far back as 1960. The quality of the archived meteorological data, however, is slightly limited relative to recent standards. To investigate ground-truth events such as volcanoes, or analyze signals having travel times greater than a couple hours, a series of files can also be generated. It was found that when providing and working with these G2S coefficient files a triangularly truncated spectral order of 120 (T-

120) is sufficient for infrasound propagation modeling. This spectral resolution translates into a horizontal spatial resolution of 1.5º. At this spectral order, each G2S coefficient file is approximately 20 MB in size.

In addition to the event driven generation of G2S coefficient files, we have developed a prototype operational processing system (G2S-RT) that produces near real-time specifications every 6 hours. The spectral resolution of these files is T-64, having an approximate global spatial resolution of 3º. Each of these G2S-RT data files is roughly 5 MB in size. We have been successfully operating this system since September 2002. The resulting G2S-RT files are pushed to the user's FTP site every 6 hours with a 48-hour delay. Automatically forwarding the data in an operational capacity requires a formal memorandum of agreement with the recipient.

Every 6 hours the G2S system autonomously obtains and archives the operation numerical weather analyses from the NOAA National Centers for Environmental Prediction (NCEP, http://www.ncep.noaa.gov). The NOAA-NCEP specification is generated from all available NOAA, DoD, and international weather monitoring network measurements and provides a detailed snapshot of the state of the entire atmosphere below 35 km at 1ºx1º resolution. A similar operational estimate can be obtained from the Navy's Fleet Numerical Meteorological and Oceanography Center (FNMOC, http://www.fnoc.navy.mil) that runs the Navy Operational Global Atmospheric Prediction System (NOGAPS). The G2S system also collects global pseudo-operational estimates of the stratosphere (10–55 km) from the NASA Global Modeling and Assimilation Office (GMAO, http://polar.gsfc.nasa.gov). This data is available for research purposes on a 24-hour delay. As with the NOAA and NOGAPS specifications, the NASA-GMAO specifications represent a synthesis of measurements from available NOAA, DoD, and NASA sensors. Finally, daily bulletins containing the measured solar 10.7 cm-1 radio flux ($F_{10.7}$) and geomagnetic activity parameters (A_p) are obtain from the NOAA/USAF Space Environment Center (SEC, http://www.sec.noaa.gov). These parameters are crucial inputs into the NRLMSISE-00 and HWM-93 portion of the G2S-RT specifications.

Model Validation Studies

Several infrasonic validation studies of the G2S model have been performed (e.g., Bhattacharyya et al., 2003) and several are ongoing. It is important that these studies cover a wide range of atmospheric configurations. In some cases the instantaneous atmospheric state will be close to its climatological state, and no differences in infrasound propagation characteristics (e.g., travel times) will be observed between calculations made with climatological models and those made from more detailed specifications. In other instances, things will be quite different.

In this symposium paper, the importance of accounting for topography and including a detailed lower atmosphere is illustrated by means of two simple comparative calculations. In the first calculation, the percentage of infrasonic energy (or ray surface area) emitted by a point source, which is transmitted though the various ducts, is calculated for the G2S and standard HWM/MSIS atmospheric specifications.

Figure 4 shows the ray turning height (z_{max}) for a hemispherical set of acoustics rays as a function of initial launch azimuth and elevation. The source was located at the surface and the atmospheric specifications shown in Figure 3 were used. Four distinct propagation modes are evident; those rays ducted in the troposphere below about 16 km (dark blue), those ducted in the stratosphere around 40–55 km (light blue), those ducted in the lower thermosphere around 110–160 km (orange), and those escaping (transparent). A local energy partitioning fraction for each of the atmospheric ducts can be defined as the total surface area of each subgroup or duct. In this example, 7.7 % of the radiated infrasound energy propagates in the troposphere, 13.2 % in the stratosphere, 61.6 % in the thermosphere, and 17.5 % escapes into the upper thermosphere. The boundaries of the four ducts are defined as; z_{max} < 20 km (tropospheric), 20 km < z_{max} < 70 km (stratospheric), 70 < z_{max} < 165 km (thermospheric), z_{max} > 165 (escape) where the altitude z is defined as true geodetic altitude, relative to mean sea level.

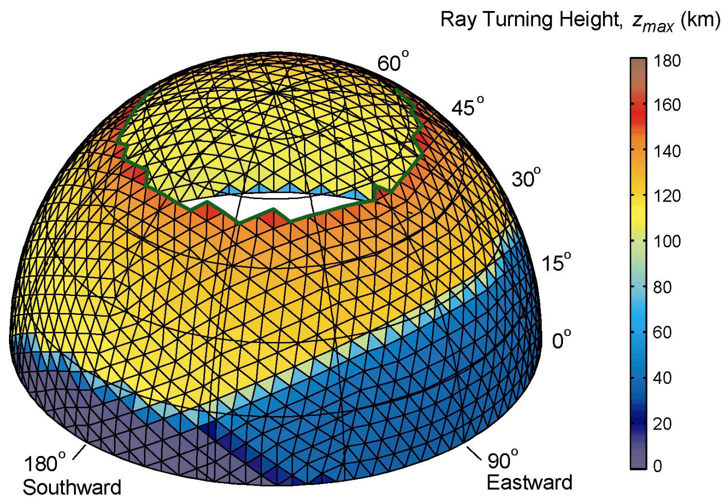

Figure 4. The turning height (z_{max}) of 2592 infrasound ray elements from an idealized isotropically radiating surface source. The ray turning heights are displayed as a function of the initial launch azimuth and elevation. The source origin is located at the center of the tessellated sphere.

Having now defined a local partitioning fraction, the calculations are preformed over a global ensemble of idealized sources to produce morphological global maps of these fractions. These maps indicate regions where tropospheric and stratospheric ducting is occurring. Figure 5 shows the global tropospheric, stratospheric, and thermospheric ducting fractions for February 27, 2000 made using; (a) the HWM-93/NRLMSISE-00 models without topography, (b) the HWM/MSIS models accounting for topography, and (c) the complete G2S atmospheric specifications including topography. A separate color scale for each duct has been defined.

While, the HWM/MSIS and NRL-G2S calculations are qualitatively similar on a global scale, there are appreciable differences on regional scales, particularly in the tropospheric ducting fractions. For all cases, the ducting fractions calculated through the HWM/MSIS models indicates that minimal tropospheric ducting exists (< 2%) in stark contrast to the G2S results. This is no surprise. The meteorological phenomenon responsible for tropospheric ducting tends toward zero when averaged over the spatiotemporal scales of the empirical models (see for example figure 7). Similar differences exist in the amounts of stratospheric ducting predicted. This difference is important because the net propagation speeds (celerity) in the tropospheric and stratospheric ducts can be significantly faster than for the thermospheric ducts. Improper phase identification would lead to errors in source locations through erroneous travel time estimates and could overwhelm operational monitoring systems with false detections.

Additionally, the meteorological specifications (e.g., NOAA-NCEP), and the HWM/MSIS and NRL-G2S models typically provide output fields at altitudes relative to mean sea level that may actually be situated below the surface of the earth. When performing infrasound propagation calculations, it is important to avoid using this part of the specifications. Relative to the calculations in Figure 5(a), the resulting ducting fractions in (b) and (c) show that infrasound originating on the Tibetan Plateau, Antarctica, and Greenland exhibits much more lower atmospheric ducting than in surrounding regions. This is especially true over Antarctica.

For high-yield events where signals travel halfway around the globe, the differences between the climatological and near real-time models may be negligible; however, for low-yield events where propagation is limited to isolated regions, the differences discussed above become important. A comprehensive discussion of the global morphology of infrasound propagation can be found in Drob et al. (2003).

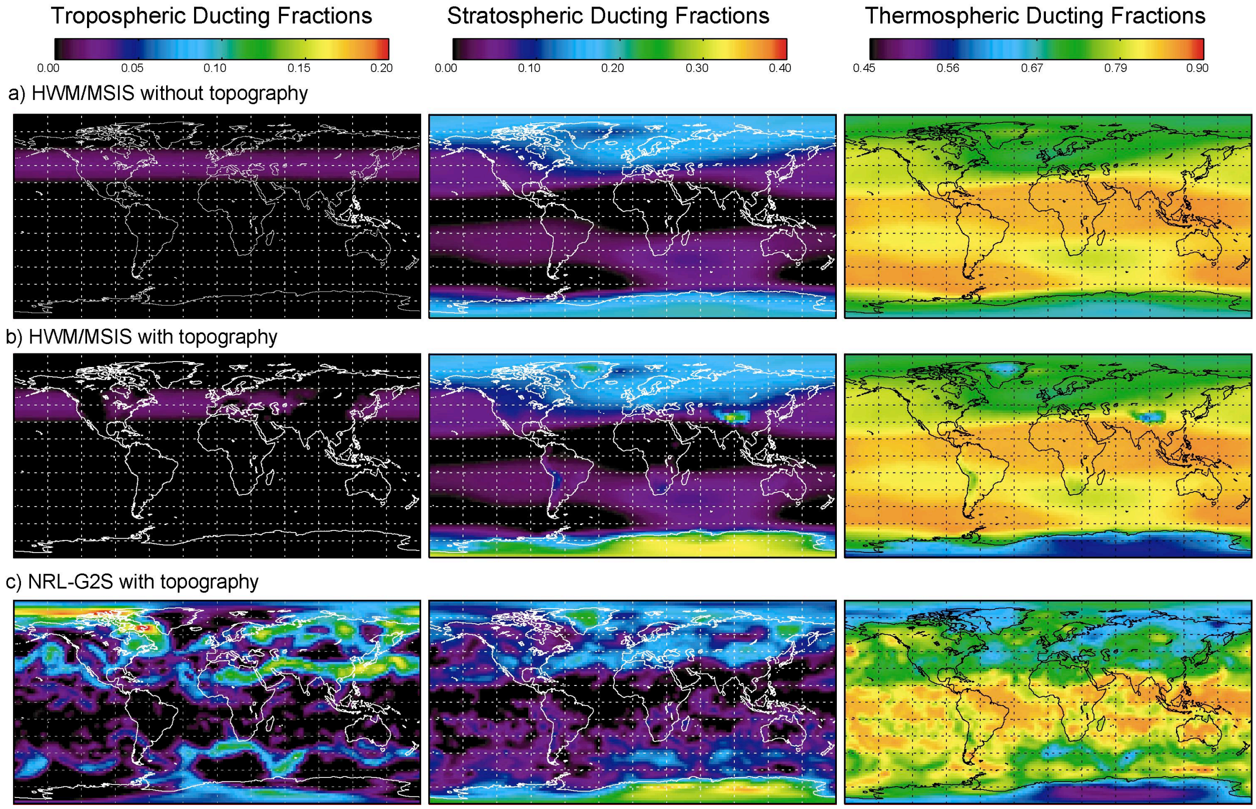

Figure 5. The February 27, 2000, 06:00 UTC tropospheric, stratospheric and thermospheric ducting fractions for a global ensemble of idealized isotropically radiating surface sources using various model assumptions. The first row (a) shows the ducting fractions calculated using the HWM/MSIS empirical model without topography. The second row (b) shows the fractions calculated using the HWM/MSIS empirical model accounting for topography. The last row (c) shows the fractions calculated using the NRL-G2S model including for topography.

A second series of calculations was performed to illustrate the behavior of infrasound propagation characteristics resulting from the day-to-day variability of the lower atmosphere as shown earlier by Garcés et al., (1999) and Le Pichon (2002). Acoustic ray-turning heights, single skip travel times, ranges, and celerity were calculated with a simple ray-tracing code (Drob et al., 2003) using both the HWM-93/NRLMSISE-00 and G2S models. The calculations were done for the first 25 days of January 2003 (00:00 UT) for an infrasound array arbitrarily located in the Southwest United States. Results from two arrival azimuths are presented in Figures 6 and 7. Figure 6 shows the corresponding HWM and G2S zonal wind profiles, derived ray-turning heights, and the effective celerity for eastward propagating infrasound signals. Figure 7 shows the corresponding HWM-93 and G2S meridional winds, ray-turning heights, and celerity for northward propagating infrasound signals.

Note the differences between the HWM/MSIS and G2S derived celerity curves. These differences are primarily caused by differences in the background wind component along the direction of propagation. For northward propagation, the calculated monthly average propagation characteristics are generally similar for both the empirical and G2S models, but some differences exist. For example, the empirical models do not predict the occasional occurrence of a northward stratospheric duct. Additional calculations are needed to quantify this. The estimated variances are, however, obviously different. For the eastward propagating waves, the estimated monthly average celerity curves also appear to be slightly different. On the other hand, the estimated variances are very different. These calculations highlight the importance of accounting for the day-to-day variability of the lower atmosphere. As a first step to account for this in current operational monitoring systems, the estimated monthly variances from the G2S calculations shown here could be used in conjunction with static climatologically derived static travel-time tables. Ultimately, near real-time G2S specification derived travel-time tables should be used operationally.

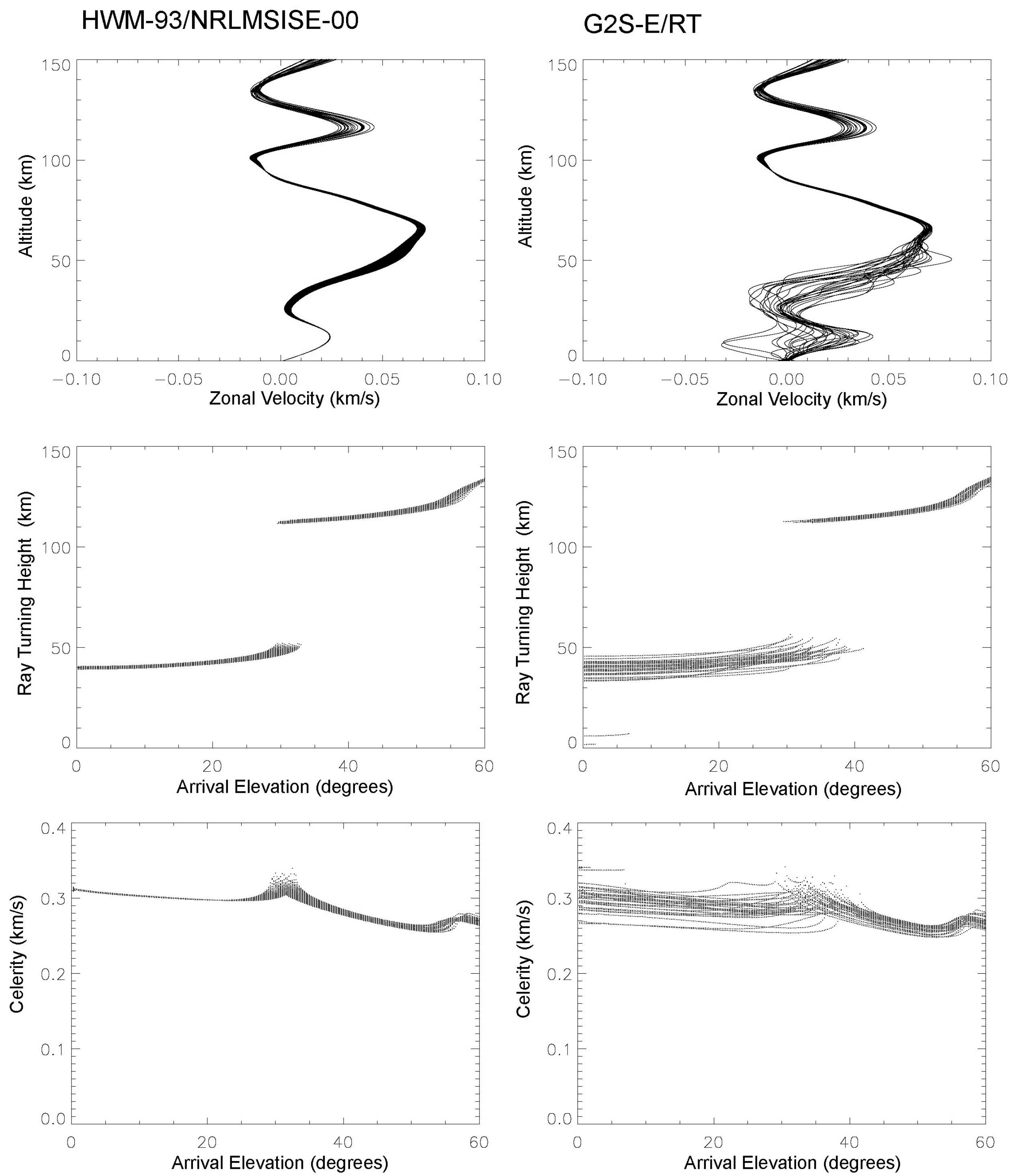

Figure 6. The HWM-93/NRLMSISE-00 (left column) and G2S (right column) zonal wind profiles (first row), derived ray turning heights (second row), and the effective celerity (third row) for infrasound signals propagating eastward. The results represent an ensemble of 00:00 UT calculations for the first 25 days in January 2003 for an infrasound array arbitrarily located in the Southwest United States.

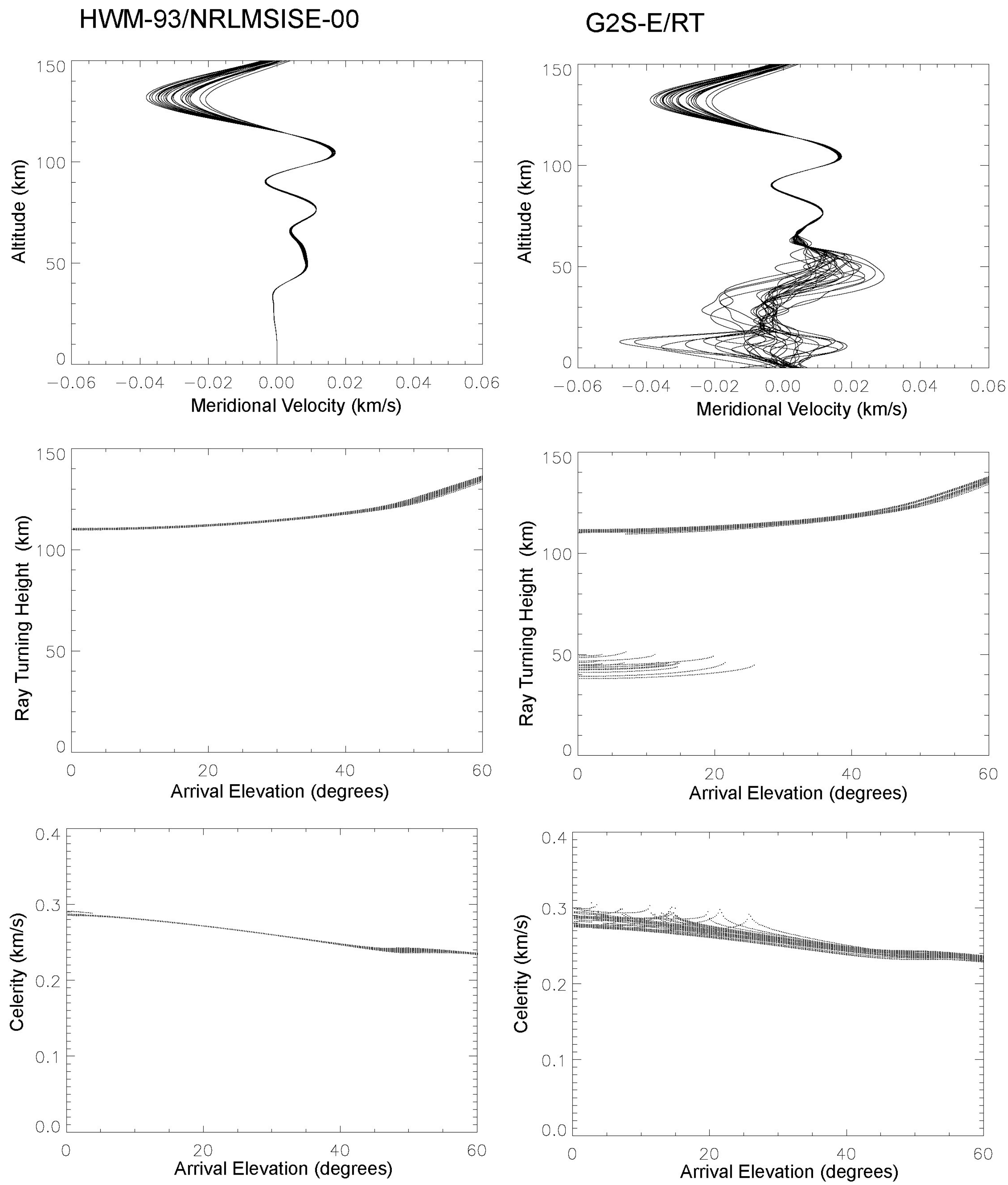

Figure 7. Same as figure 6, but for infrasound signals propagating northward.

CONCLUSIONS AND RECOMMENDATIONS

This work seeks to demonstrate the importance of having accurate atmospheric specifications, starting at the source level for nuclear monitoring. If the initial conditions (e.g., improperly specified source altitude and surface conditions) or the intervening atmospheric profiles are inaccurate, then inaccurate estimates of ducting heights, travel times, and source locations will result. Therefore, in order to accurately relate regional infrasound propagation calculations to microbarograph observations, the use of detailed atmospheric specifications and topography is highly recommended.

In shifting away from climatologically based atmospheric profiles, however, a great deal of complexity is introduced into the problem of infrasound propagation modeling. This complexity arises from the natural variability of the atmosphere across all levels. It has time scales from several hours to several months and horizontal scales of roughly 750 km. We have demonstrated with a simple model that it is now possible to account for this complexity.

The NRL-Ground to Space G2S semi-empirical spectral model seeks to combine numerous sparse datasets in a self-consistent manner to specify the details of the entire atmosphere for infrasound propagation calculations and specifically nuclear explosion monitoring. This new model includes important latitudinal, longitudinal, and daily variability as given by historical and near-real-time operational data. The system seeks to encapsulate and compress the available information, providing a very efficient way to store, transmit, and reconstruct large global volumes of environmental data.

For infrasound applications, G2S is meant to replace the HWM-93/NRLMSISE-00 models as the next generation semi-empirical atmospheric specification tool. There are some known issues regarding the tidal amplitudes and phases of empirical models during certain times of the year that the current version of G2S model does not address (Drob and Picone, 2000). These tidal phases strongly influence the behavior of thermospheric phases. In the absence of G2S specifications, the underestimation of the lower and middle atmospheric wind jets by the empirical models is also of importance to infrasound propagation modeling (Drob and Picone, 2000). The adjustment or updating of the current HWM-93/NRLMSISE-00 internal model coefficients thus remains a top priority. The empirical models serve as the backbone of the G2S model, are easy to use, and adequate for some monitoring applications.

Finally, no measurement or model is perfect, especially when considered individually. While the meteorological specifications and empirical atmospheric models used in the study have been validated in numerous ways, the ultimate substantiation of the conclusions, and future work, should involve the analysis of infrasonic ground-truth events observed by infrasound monitoring networks. It is also felt that it is important to continue this evaluation with a host of different propagation models such as normal modes, ray tracing, and parabolic equations. Furthermore, side-by-side comparison of specifications of the BBN InfraMAP method of combining NOGAPS specification with the HWM-93/NRLMSISE-00 model will be important.

ACKNOWLEDGEMENTS

User feedback and beta testing was provided by Claus Hertzer and Milton Garces of ISLA, and Galina Rovner and Gerald D'Spain of UCSD. Additional ideas, model application, and feedback were also provided Joydeep Bhattacharyya and others at CMR/SAIC. Discussions with Rob Gibson and David Norris of BBN technologies on defining the G2S external library programming interface and G2S output fields were also helpful. Everyone's efforts and contributions are greatly appreciated. I would also like to thank the NASA Goddard Space Flight Center, Global Modeling and Assimilation Office (GSFC-GMAO), and the NOAA National Centers for Environmental Predication (NCEP) for making their meteorological products available for this research.

REFERENCES

Bhattacharyya, J., H. Bass, D.P. Drob, R.W. Whitaker, D.O. ReVelle, and T. Sandoval (2003), Description and Analysis of Infrasound and Seismic Signals Recorded from the Watusi Explosive Experiment on September 28, 2002, *Current Proceedings.*

Drob, D. P., J.M. Picone, and M.A. Garcés (2003), The Global Morphology of Infrasound Propagation, *J. Geophys. Res.*, in press.

Drob D.P., and J.M. Picone, Statistical Performance Measures of the HWM-93 And MSISE-90 Empirical Atmospheric Models and the Relation to Infrasonic CTBT Monitoring (2000), *Proceedings of the 22nd Annual DoD/DOE Seismic Research Symposium: Planning for Verification of and Compliance with the Comprehensive Nuclear-Test-Ban Treaty (CTBT)*, New Orleans, LA, no.07-03, 8 pages.

Garcés, M., R. Hansen, K. Lindquist, D. Drob, and M. Picone (1999), Variability of the Lower Atmosphere and Its Effect on the Propagation of Infrasonic Waves, Proceedings of the 21st, Annual Research Symposium on Monitoring a Comprehensive Test Ban Treaty, Los Alamos National Laboratory - LA-UR-99-4700, 105-111.

Garcés, M., C. Hetzer, K. Lindquist, and D. Drob (2002), Source Location Algorithm for Infrasonic Monitoring, *Proceedings of the 24th Seismic Research Review – Nuclear Explosion Monitoring: Innovation and Integration,* Ponte Vedra, FL, Los Alamos National Laboratory - LA-UR-02-5048, 755-765.

Gibson, G.G. and D.E. Norris, Integration of Near-Real-Time Atmospheric Models with InfraMAP and Applications to Modeling Infrasound from Rockets (2002), *Proceedings of the 24th Seismic Research Review – Nuclear Explosion Monitoring: Innovation and Integration*, Ponte Vedra, FL, Los Alamos National Laboratory - LA-UR-02-5048, 775-782.

Hedin, A. E, E. L. Fleming, A. H. Manson, F. J. Schmidlin, S. K. Avery, R. R. Clark, S. J. Franke, G. J. Fraser, T. Tsuda, F. Vial, and R. A. Vincent (1996), Empirical wind model for the upper, middle, and lower atmosphere, *J. Atmos. Terr. Phys*., 58, 1421-1447.

Le Pichon, A., M. Garces, E. Blanc, M. Barthélémy, and D. Drob, (2002), Acoustic propagation and atmosphere characteristics derived from infrasonic waves generated by the Concorde, *J. Acoust. Soc. Am.*, 111 (1), 629-641.

Picone, J.M., A.E. Hedin, D.P. Drob, and A.C. Aikin (2002), NRLMSISE-00 Empirical model of the atmosphere: statistical comparisons and scientific issues, *J. Geophys. Res.*, 107 (A12): art. no. 1468.